LWRS Newsletter
Light Water Reactor Sustainability
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Light Water Reactor Sustainability Program Integrated Program Plan

Kathryn McCarthy
Director, LWRS Technical Integration Office

The Light Water Reactor Sustainability (LWRS) Program Integrated Program Plan was released on January 31, 2012; it can be downloaded at https://inlportal.inl.gov/portal/server.pt/document/98831/inl-ext-11-23452_lwrs_program_plan_01-31-12_pdf. The Integrated Program Plan describes the LWRS Program objectives, technical plans, and interfaces with our industry partners and other Department of Energy (DOE) programs. It also includes an overview of each of the LWRS Pathways and a description of major deliverables to be completed by each pathway, with an emphasis on deliverables between now and 2016. This article provides a brief summary of the LWRS Program Integrated Program Plan.

Introduction

The LWRS Program is the primary programmatic activity that addresses Objective 1 ("Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of the current reactors") in the 2010 DOE Nuclear Energy Research and Development Roadmap. For the purpose of the LWRS Program, "sustainability" is defined as the ability to maintain safe and economic operation of the existing fleet of nuclear power plants for a longer-than-initially-licensed lifetime. It has two facets with respect to long-term operations: (1) manage the aging of plant systems, structures, and components so that nuclear power plant lifetimes can be extended and the plants can continue to operate safely, efficiently, and economically; and (2) provide science-based solutions to the industry to implement technology to exceed the performance of the current labor-intensive business model.

An important aspect of the LWRS Program is partnering with industry and the Nuclear Regulatory Commission to support and conduct the long-term research needed to inform major component refurbishment and replacement strategies, performance enhancements, plant license extensions, and age-related regulatory oversight decisions. The DOE research, development, and demonstration role focuses on aging phenomena and issues that require long-term research, unique DOE laboratory expertise and facilities, and are applicable to all operating reactors. When appropriate, demonstration activities will be cost shared with industry or the Nuclear Regulatory Commission.

The LWRS Program is focused on the following three goals:

- Developing the fundamental scientific basis to understand, predict, and measure changes in materials and systems, structures, and components as they age in environments associated with continued long-term operations of the existing reactors
- Applying this fundamental knowledge to develop and demonstrate methods and technologies that support safe and economical long-term operation of existing reactors
- Researching new technologies to address enhanced plant performance, economics, and safety.

Program Research and Development Interfaces

Planning, execution, and implementation of the LWRS Program are done in coordination with the nuclear industry, Nuclear Regulatory Commission, universities, and related DOE research and development programs (e.g., Nuclear Energy Advanced Modeling and Simulation, Consortium for Advanced Simulation of Light Water Reactors (LWRs), and the Fuel Cycle Research and Development Program) to assure relevance and effective management of the work. Coordination with our partners (Figure 1) is essential to the success of the LWRS Program.

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Materials Aging and Degradation

Nuclear reactors present a very challenging service environment. Components within the containment of an operating reactor must tolerate high-temperature water, stress, vibration, and an intense neutron field. Degradation of materials in this environment can lead to, in some cases, reduced performance and failures. Materials degradation in a nuclear power plant is extremely complex due to the various materials, environmental conditions, and stress states. Over 25 different metal alloys can be found within the primary and secondary systems. Additional materials exist in concrete; the containment vessel; instrumentation, information, and control systems equipment; cabling; buried piping; and other support facilities. Dominant forms of degradation may vary greatly between the different systems, structures, and components and can have an important role in the safe and efficient operation of a nuclear power plant.

The Materials Aging and Degradation Pathway includes research and development to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. The work will provide data and methods to assess the performance of systems, structures, and components essential to safe and sustained nuclear power plant operations. The research and development products will be used to define operational limits and aging mitigation approaches for materials in nuclear power plant systems,

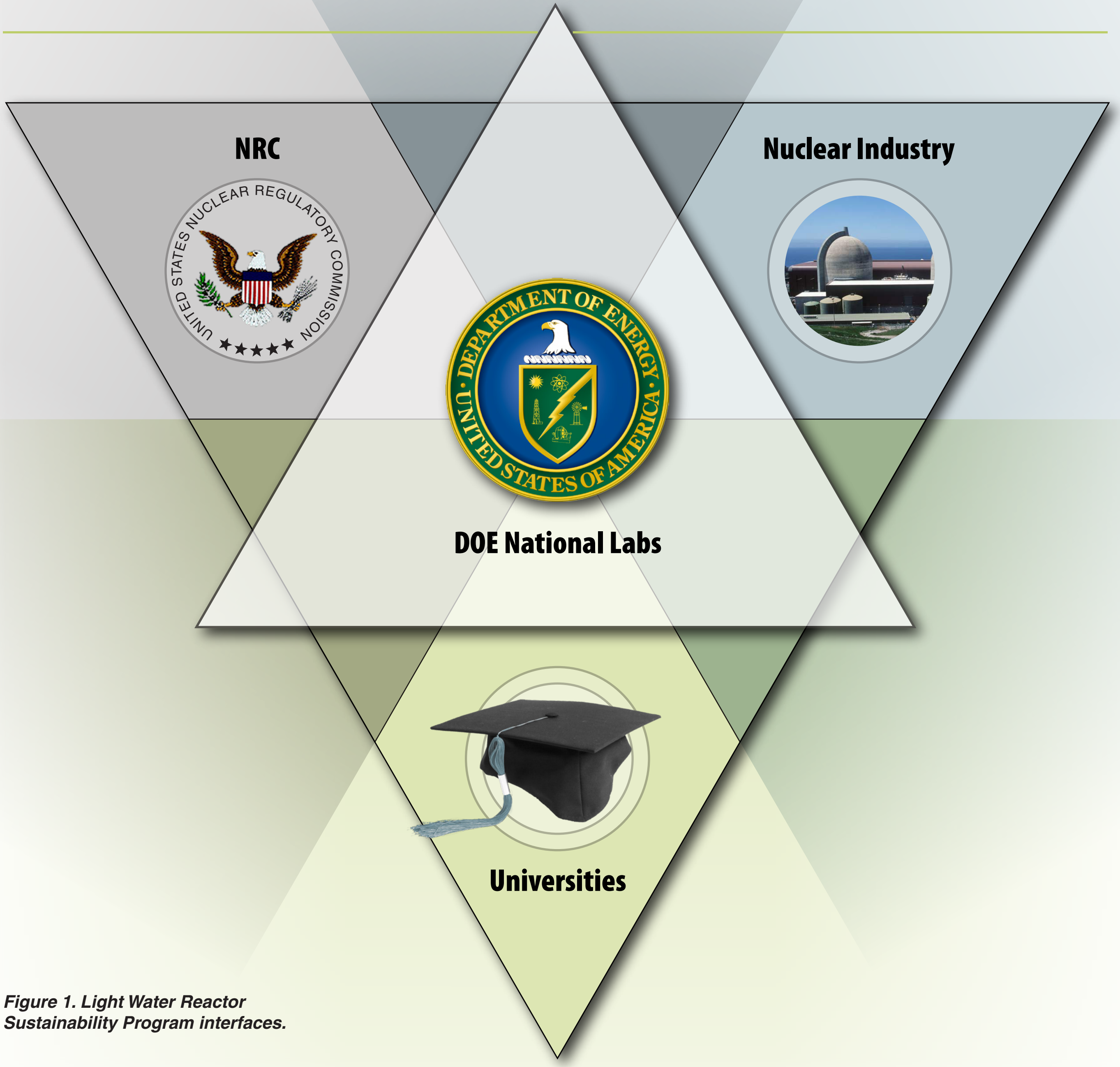

Figure 1. Light Water Reactor Sustainability Program interfaces.

structures, and components subject to long-term operating conditions.

The following topics are covered under this pathway:

- Reactor materials
  - Mechanisms of irradiation-assisted stress corrosion cracking
  - High-fluence effects on reactor pressure vessel steels
  - Precursor states (e.g., damage from grinding, polishing, and installation) and their influence on crack-initiation in nickel-based alloys used as piping in nuclear power plants
  - Effects and magnitude of irradiation-assisted stress corrosion cracking at very high fluences
  - Evaluation of risk for high-fluence core internal components to swelling
  - Evaluation of risk for high-fluence core internal components to embrittlement due to phase transformations
  - Extending the mechanistic understanding of irradiation effects on reactor pressure vessel steels
  - Environmentally assisted fatigue mechanisms to predict life for this mechanism
  - Techniques for nondestructive examination of key reactor metals
- Concrete
  - Mechanisms of concrete degradation
  - Techniques for nondestructive examination of concrete
- Cabling
  - Mechanisms of cable degradation
  - Techniques for nondestructive examination of cables
- Mitigation technologies
  - Weld repair
  - Assessment of thermal annealing as a mitigation technology for reactor pressure vessel and core internal embrittlement
  - Advanced replacement alloys.

Service materials from active or decommissioned nuclear power plants will be used to assess degradation models to further develop the scientific basis for understanding and predicting long-term environmental degradation behavior.

A high-level summary of the milestones for the Materials Aging and Degradation Pathway is shown in Figure 2. Detailed year-by-year milestones can be found in the LWRS Program Integrated Program Plan.

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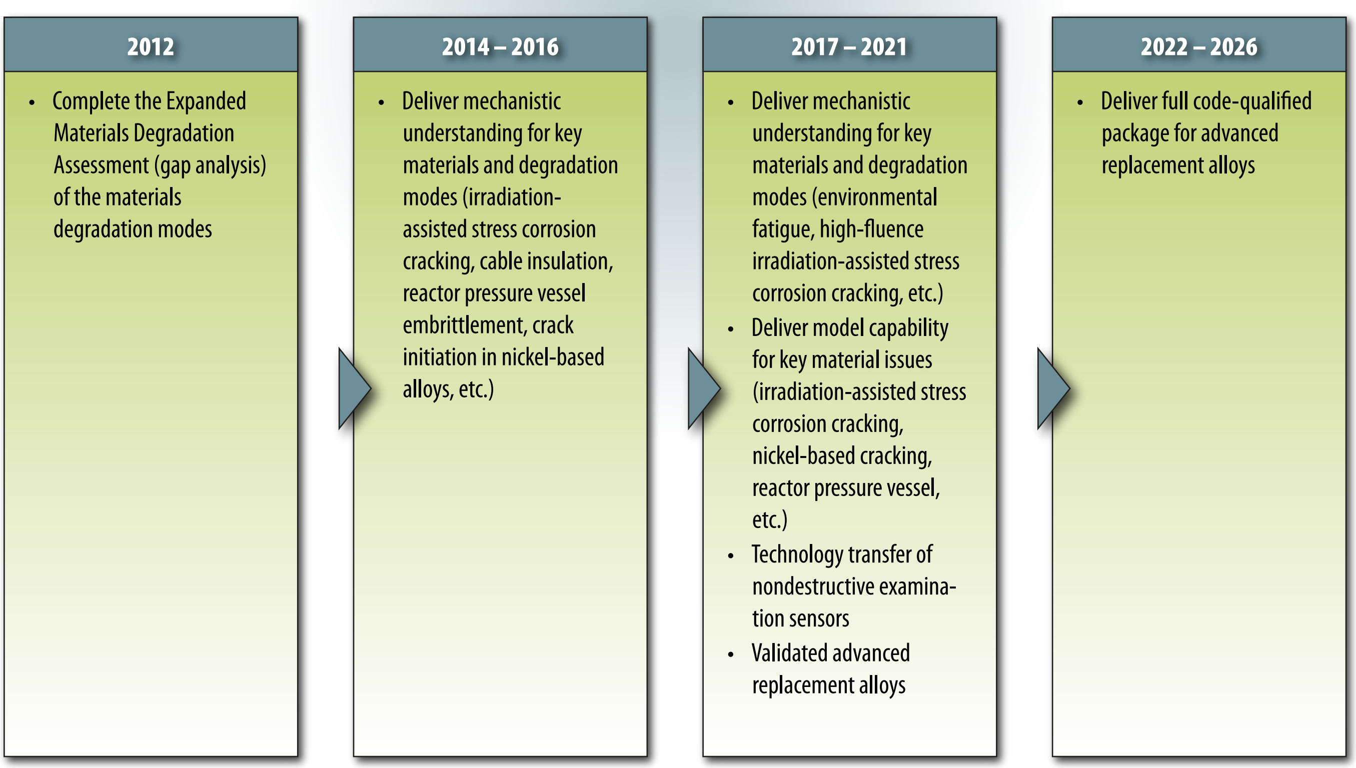

2012

- Complete the Expanded Materials Degradation Assessment (gap analysis) of the materials degradation modes

2014 – 2016

- Deliver mechanistic understanding for key materials and degradation modes (irradiation-assisted stress corrosion cracking, cable insulation, reactor pressure vessel embrittlement, crack initiation in nickel-based alloys, etc.)

2017 – 2021

- Deliver mechanistic understanding for key materials and degradation modes (environmental fatigue, high-fluence irradiation-assisted stress corrosion cracking, etc.)
- Deliver model capability for key material issues (irradiation-assisted stress corrosion cracking, nickel-based cracking, reactor pressure vessel, etc.)
- Technology transfer of nondestructive examination sensors
- Validated advanced replacement alloys

2022 – 2026

- Deliver full code-qualified package for advanced replacement alloys

Figure 2. Summary of Materials Aging and Degradation Pathway milestones.

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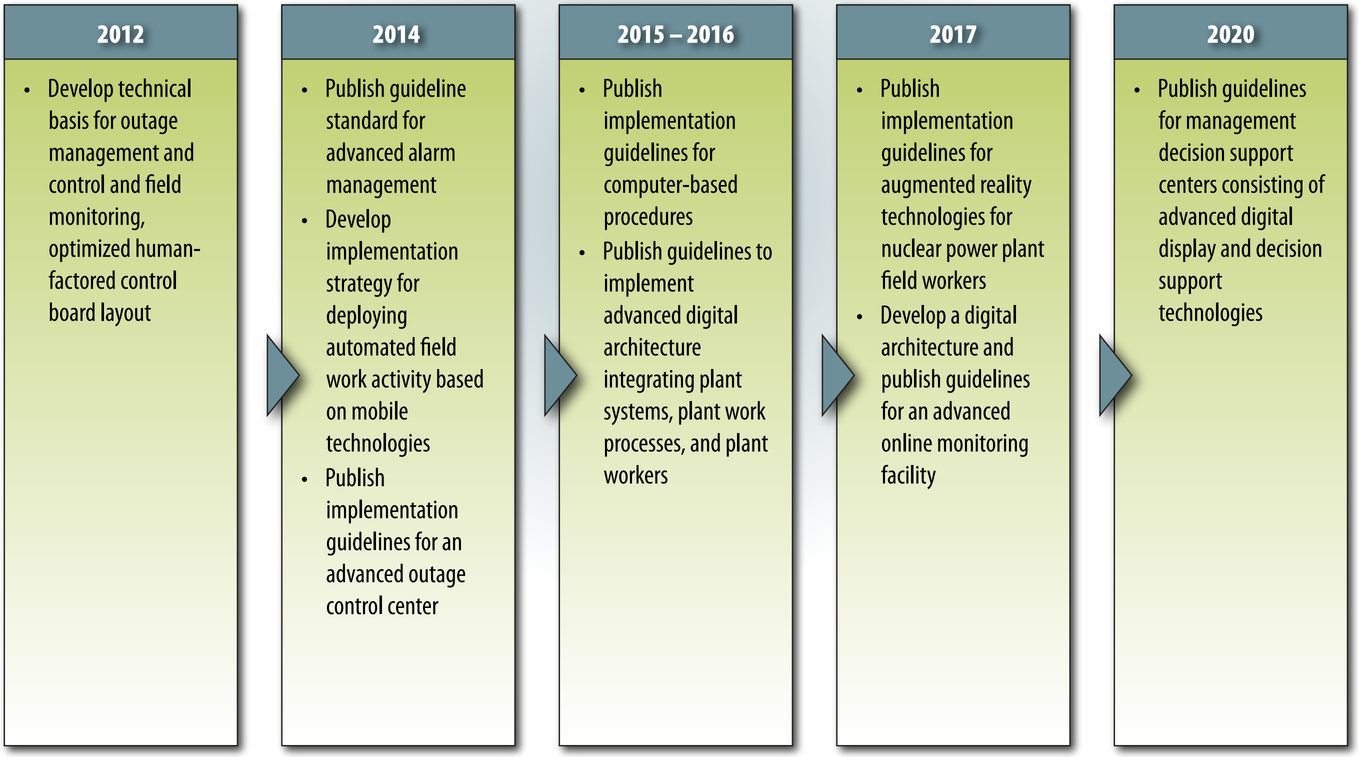
Advanced Instrumentation, Information, and Control Systems Technologies

Reliable instrumentation, information, and control systems technologies are essential to ensuring safe and efficient operation of the U.S. LWR fleet. These technologies affect every aspect of nuclear power plant and balance-of-plant operations. In 1997, the National Research Council conducted a study concerning the challenges involved in modernization of digital instrumentation and control systems in nuclear power plants. Their findings identified the need for new instrumentation, information, and control systems technology integration. Today, digital technologies are implemented as point solutions to performance concerns with individual instrumentation, information, and control systems components. This reactive approach is characterized by planning horizons that are short and typically only allow for 'like-for-like' replacements. This results in a fragmented, non-optimized approach that is driven by immediate needs. As a long-term strategy, this is inefficient in light of the evolution of instrumentation, information, and control systems technology, the availability of skills needed to maintain this legacy technology, and the associated high costs and uncertainties.

The purpose of this research pathway is to enable modernization of the legacy instrumentation, information, and control systems in a manner that creates a seamless digital environment that encompasses all aspects of plant operations and support – building a three-dimensional information architecture that integrates plant systems, plant processes, and plant workers in an array of interconnected technologies as follows:

- Plant systems – beyond the monitoring and control functions of these systems, extend plant information within these systems directly into the processes that support the plant work activities and directly to the workers performing these activities.
- Plant processes – integrate processes with real-time plant information to enable task automation, plant status control, more accurate procedure and work package usage, enhanced risk management, and other such functions, based on actual plant configuration, performance, and operational constraints.



2012

- Develop technical basis for outage management and control and field monitoring, optimized human-factored control board layout

2014

- Publish guideline standard for advanced alarm management
- Develop implementation strategy for deploying automated field work activity based on mobile technologies
- Publish implementation guidelines for an advanced outage control center

2015 – 2016

- Publish implementation guidelines for computer-based procedures
- Publish guidelines to implement advanced digital architecture integrating plant systems, plant work processes, and plant workers

2017

- Publish implementation guidelines for augmented reality technologies for nuclear power plant field workers
- Develop a digital architecture and publish guidelines for an advanced online monitoring facility

2020

- Publish guidelines for management decision support centers consisting of advanced digital display and decision support technologies

Figure 3. Summary of Advanced Instrumentation, Information, and Control Systems Technologies Pathway milestones.

- Plant workers – immerse plant workers in an information-rich environment that provides immediate, accurate plant information and allows the workers to conduct plant processes directly at the plant location, using mobile technologies, augmented reality (e.g., “seeing” radiation fields), and real-time video, which enables virtual collaboration and collective situational awareness among all participants in a work activity, both at the job site and in remote locations.

The following topics are covered under this pathway:

- Development, demonstration, and deployment of new digital technologies for instrumentation and control architectures and providing monitoring capabilities to ensure the continued safe, reliable, and economic operation of the nation’s operating nuclear power plants
  - Reliable digital instrumentation, information, and control systems technologies are essential to life extension
  - New technologies to monitor and characterize the effects of aging and degradation in structures and components
- Development of capabilities to support long-term nuclear power plant operations and management
  - Support creation of new technologies that can be deployed to address the sustainability of today’s instrumentation, information, and control systems technologies
  - Improve understanding of, confidence in, and facilitate transition to these new technologies
  - Support development of the technical basis needed to achieve technology deployments
  - Create or renew infrastructure needed for research, education, and testing
- Advanced instrumentation, information, and control systems technologies
  - Reduce the technical, financial, and regulatory risk of upgrading the aging instrumentation, information, and control systems to support extended plant life beyond 60 years
  - Provide the technological foundation for a transformed nuclear power plant operating model that improves plant performance and addresses the challenges of the future business environment
- Work activities are grouped into the following major areas of enabling capabilities:
  - Highly integrated control room
  - Highly automated plant
  - Integrated operations
  - Human performance improvement for field workers
  - Outage safety and efficiency
  - Centralized online monitoring and information integration
- Carrying out a series of pilot projects to collectively integrate new technologies into nuclear power plant work activities.

A high-level summary of the milestones for the Advanced Instrumentation, Information, and Control Systems Technologies Pathway is shown in Figure 3. Detailed year-by-year milestones can be found in the LWRS Program Integrated Program Plan.

Risk Informed Safety Margin Characterization

Safety is central to the design, licensing, operation, and economics of nuclear power plants. As the current LWR nuclear power plants age beyond 60 years, there are possibilities for increased frequency of systems, structures, and components failures that initiate safety-significant events, reduce existing accident mitigation capabilities, or create new failure modes. Plant designers commonly “over-design” portions of nuclear power plants and provide robustness in the form of redundant and diverse engineered safety features to ensure that, even in the case of well-beyond design basis scenarios, public health and safety will be protected with a very high degree of assurance. This form of defense-in-depth is a reasoned response to uncertainties and is often referred to generically as “safety margin.” Historically, specific safety margin provisions have been formulated, primarily based on “engineering judgment.”

The ability to better characterize and quantify safety margin holds the key to improved decision-making about LWR design, operation, and plant life extension. In addition, as research and development in the LWRS Program and other collaborative efforts yield new data and improved scientific understanding of physical processes that govern the aging and degradation of plant systems, structures, and components (and concurrently support technological advances in nuclear reactor fuels and plant instrumentation, information, and control systems), needs and opportunities to better optimize plant safety and performance will become known.

This pathway will develop and deploy approaches to support management of uncertainty in safety margins quantification to improve decision-making for nuclear power plants. Management of uncertainty implies the ability to (a) understand and (b) control risks related to safety. Consequently, the Risk-Informed Safety Margin

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Characterization Pathway is dedicated to improving both aspects of safety management.

The following topics are covered under this pathway:

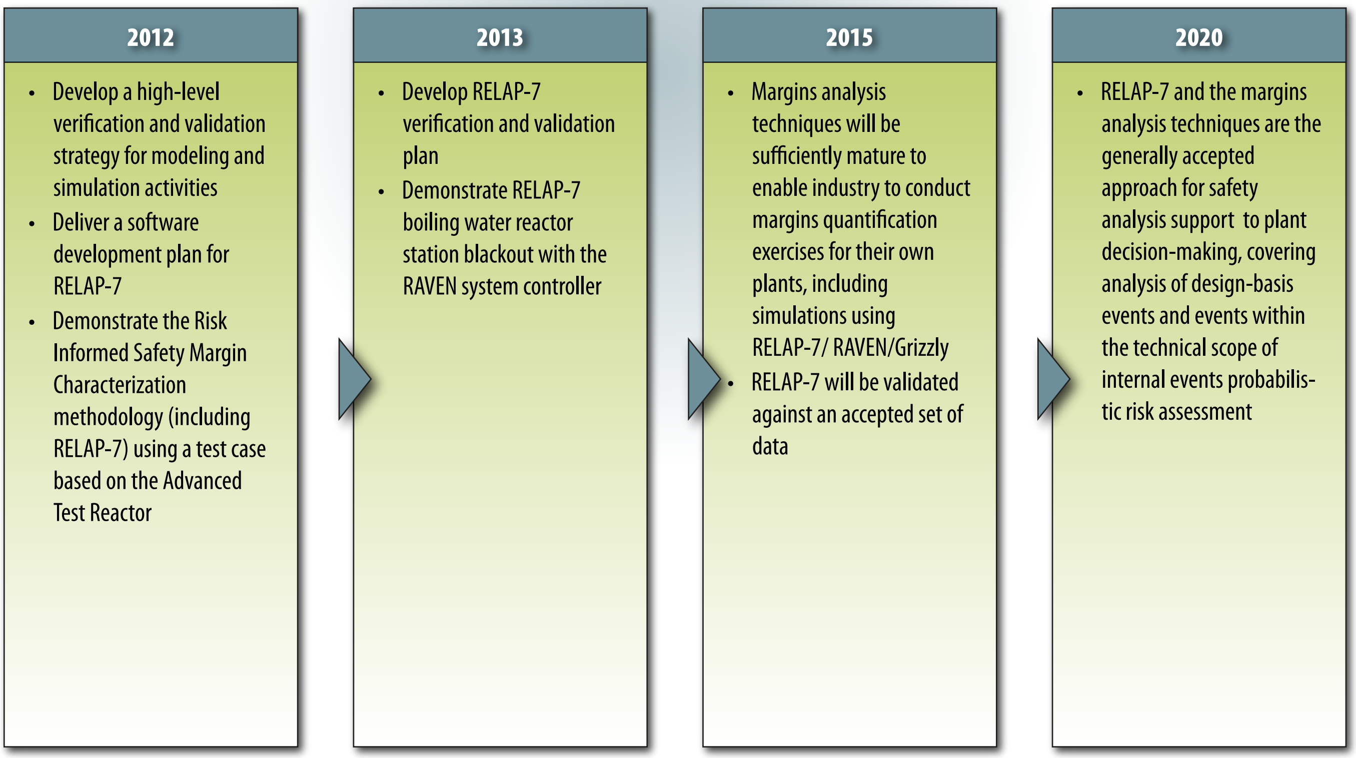
- Margins analysis techniques
  - Develop techniques to conduct more accurate margins analysis, including a methodology for carrying out simulation-based studies of margin
- Simulation components of the risk-informed safety margin characterization toolkit
  - RELAP-7
    - Systems code that will simulate behavior at the plant level
    - Advanced computational tools and techniques to allow faster and more accurate analysis
  - Simulation controller (RAVEN – Reactor Analysis and Virtual control Environment)
    - Provides input on plant state to RELAP-7 (including operator actions, component states, etc.)
    - Integrates output from RELAP-7 with other considerations to determine component states
  - Aging simulation
    - Component aging and damage evolution will be modeled in separate modules that will couple to RELAP-7 and RAVEN.

A high-level summary of the milestones for the Risk Informed Safety Margin Characterization Pathway is shown in Figure 4. Detailed year-by-year milestones can be found in the LWRS Program Integrated Program Plan.

Advanced Light Water Reactor Nuclear Fuels

Nuclear fuel performance is a significant driver of nuclear power plant operational performance, safety, operating economics, and waste disposal requirements. Over the past two decades, the nuclear power industry has improved plant capacity factors with incremental improvements achieved in fuel reliability and burnup. However, these upgrades are reaching their maximum achievable impact within the constraints of the existing fuel designs, materials, licensing, and enrichment limits.

The Advanced LWR Nuclear Fuels Pathway is developing advanced cladding designs and computational models to predict fuel performance. The focus is on developing the



2012

- Develop a high-level verification and validation strategy for modeling and simulation activities
- Deliver a software development plan for RELAP-7
- Demonstrate the Risk Informed Safety Margin Characterization methodology (including RELAP-7) using a test case based on the Advanced Test Reactor

2013

- Develop RELAP-7 verification and validation plan
- Demonstrate RELAP-7 boiling water reactor station blackout with the RAVEN system controller

2015

- Margins analysis techniques will be sufficiently mature to enable industry to conduct margins quantification exercises for their own plants, including simulations using RELAP-7/ RAVEN/Grizzly
- RELAP-7 will be validated against an accepted set of data

2020

- RELAP-7 and the margins analysis techniques are the generally accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of internal events probabilistic risk assessment

Figure 4. Summary of Risk Informed Safety Margin Characterization Pathway milestones.

scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants and applying the information to development of high-performance, high-burnup fuels with improved safety, cladding, integrity, and nuclear fuel cycle economics. Silicon carbide ceramic matrix composite materials are the leading cladding option for LWR fuels under investigation in this pathway because of their potential for significant improvements in performance. Direct cooperation with the DOE Fuel Cycle Research and Development Program is important to the success of this pathway. The Fuel Cycle Research and Development Program investigates additional fuel and cladding options and performs evaluations of fuel cycle issues related to economics, fabrication, recycling, and storage of advanced fuel options.

The following topics are covered under this pathway:

- Silicon carbide ceramic matrix composite designs and concepts
  - Increase the understanding of advanced LWR fuel design concepts and apply this understanding to create safer and more economic nuclear fuel
  - Perform a sequence of increasingly complex out-of-pile and in-pile tests to understand and demonstrate performance
- Mechanistic understanding of fuel behavior – model development
  - Develop a fuel mechanical property change model as a function of exposure
  - Develop a pellet cladding interaction model
  - Develop mesoscale models of microstructure fuel behavior
- Advanced tools
  - Develop fuel performance tools, including mechanical models of composite cladding and design studies of advanced silicon carbide cladding
  - Perform experiments to verify design and safety margin calculation tools.

A high-level summary of the milestones for the Advanced LWR Nuclear Fuels Pathway is shown in Figure 5. Detailed year-by-year milestones can be found in the LWRS Program Integrated Program Plan.

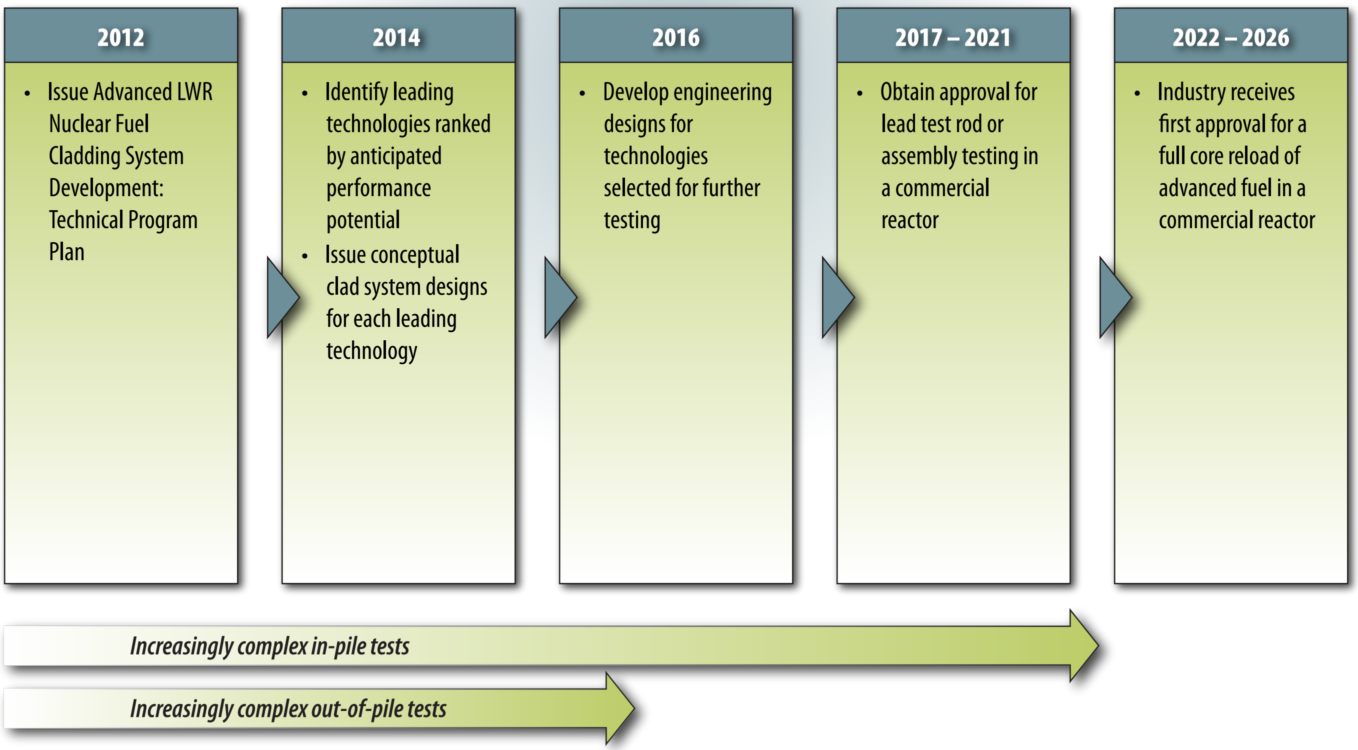


Figure 5. Summary of Advanced LWR Nuclear Fuels Pathway milestones.

Development and Characterization of Advanced Nuclear Fuel Cladding

Isabella J. van Rooyen
Advanced LWR Nuclear Fuels
Pathway

Shannon M. Bragg-Sitton
Advanced LWR Nuclear Fuels
Pathway Lead

Nuclear fuel performance is a significant driver of nuclear power plant operational performance, safety, economics, and waste disposal requirements. The Advanced LWR Nuclear Fuels Pathway focuses on improving the scientific knowledge basis to enable the development of high-performance, high burn-up fuels with improved safety and cladding integrity and improved nuclear fuel cycle economics. To achieve significant improvements, fundamental changes are required in the areas of nuclear fuel composition, cladding integrity, and fuel/cladding interaction.

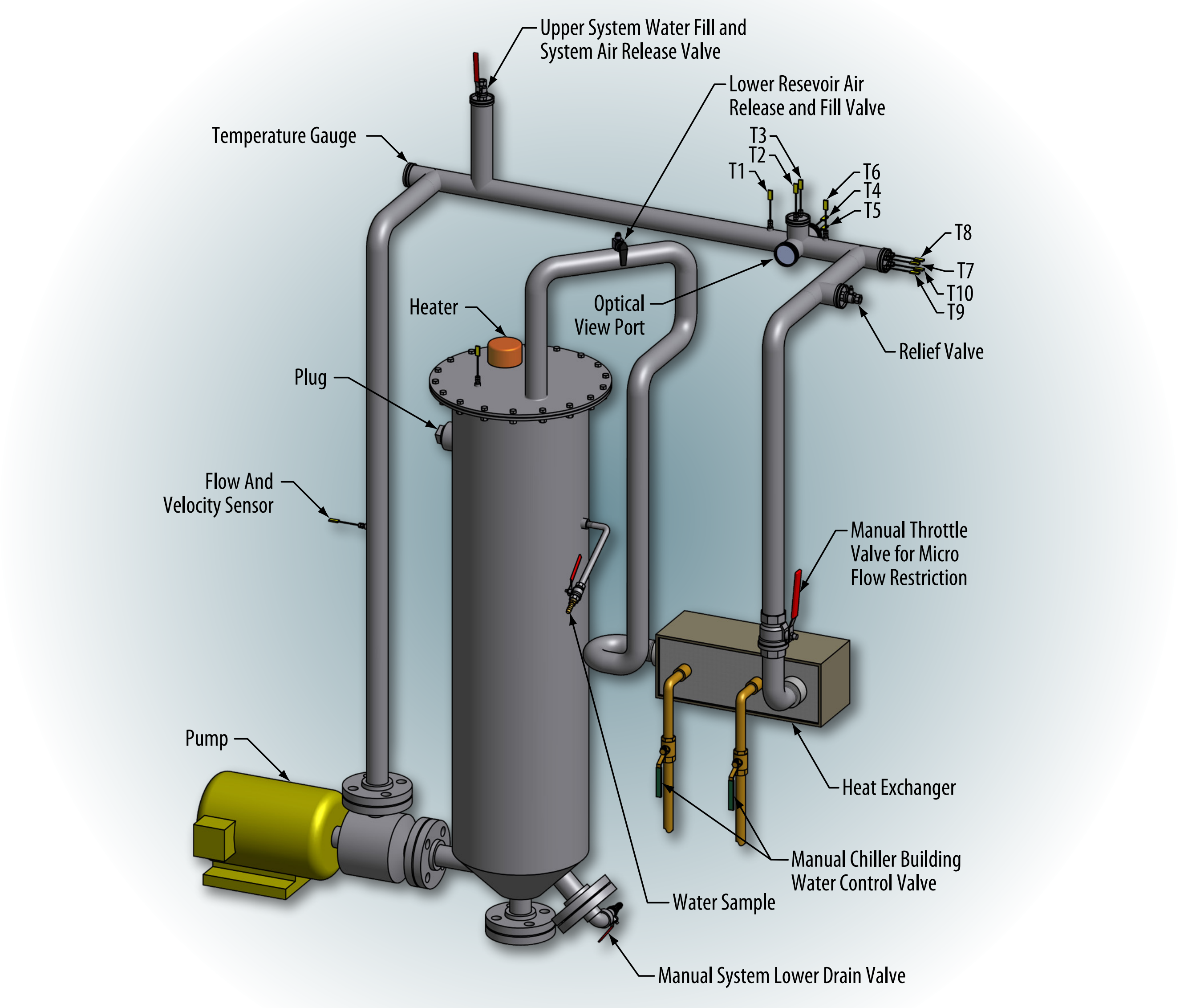


Figure 6. Diagram of the hot water corrosion flow test system at Idaho National Laboratory; test samples are installed in the top leg of the flow loop at the optical view port position.

Selection of alternate cladding and structural materials must first take into account physical (geometric) and chemical compatibility with currently operating LWR designs. Cladding options under consideration have focused on the use of silicon carbide (SiC). Both monolithic SiC and SiC composite have been studied by a variety of international research programs, resulting in a substantial body of data available to guide the current LWRS Program effort. Early research in the Advanced LWR Nuclear Fuels Pathway has focused on developing a better understanding of SiC ceramic matrix composite (CMC). The final clad design could be fully ceramic or a "hybrid" design, which would incorporate SiC as a structural material supplementing an inner metal tube (possibly Zircaloy-4).

The LWRS Program Fuel Development Plan, currently being drafted, focuses on addressing critical path items in fielding advanced clad technology. In addition to an appropriate level of mechanistic and systems-level modeling, significant out-of-pile testing is anticipated to fully characterize mechanical, physical, and chemical properties of candidate materials and designs and to demonstrate performance under nominal operating conditions and postulated accident conditions. Non-nuclear tests will provide a basis for initial downselection of candidate advanced cladding designs. As appropriate, where critical path items require targeted irradiations, these will be carried out in support of the development effort.

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Figure 7. Photo of the assembled hot water corrosion flow test equipment.

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Materials Characterization Test Plan

A series of out-of-pile tests will be performed to fully characterize candidate materials. Advanced cladding materials must provide substantial benefit over the current zirconium-based cladding (e.g., Zircaloy-4, Zircaloy-2, ZIRLO, etc.). The planned tests are intended to either produce quantitative data or to demonstrate the properties required to achieve the following two initial

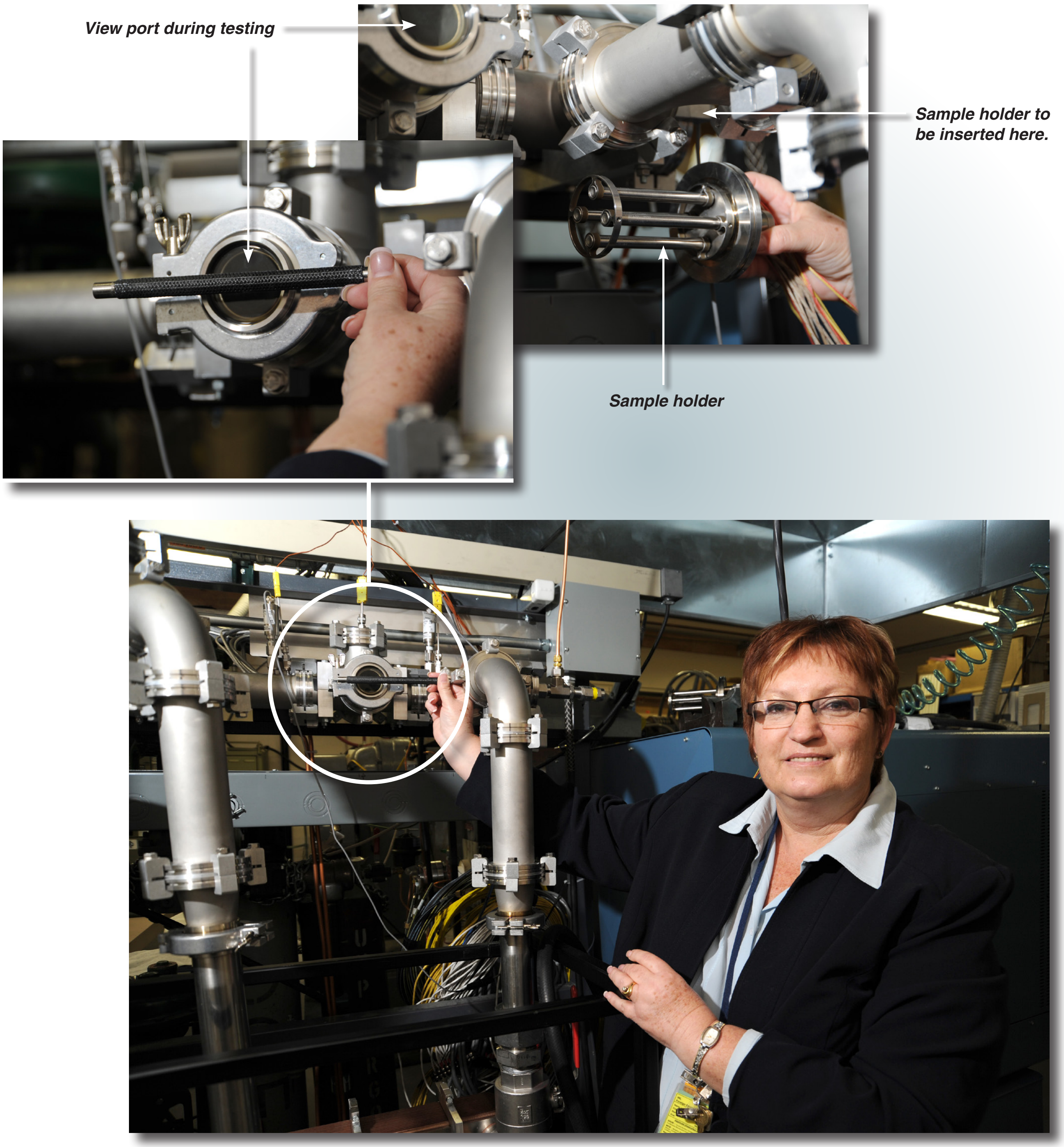

Figure 8. Researcher Isabella van Rooyen showing the position of the sample during testing and photos showing the sample holder, which can hold up to four samples during testing.

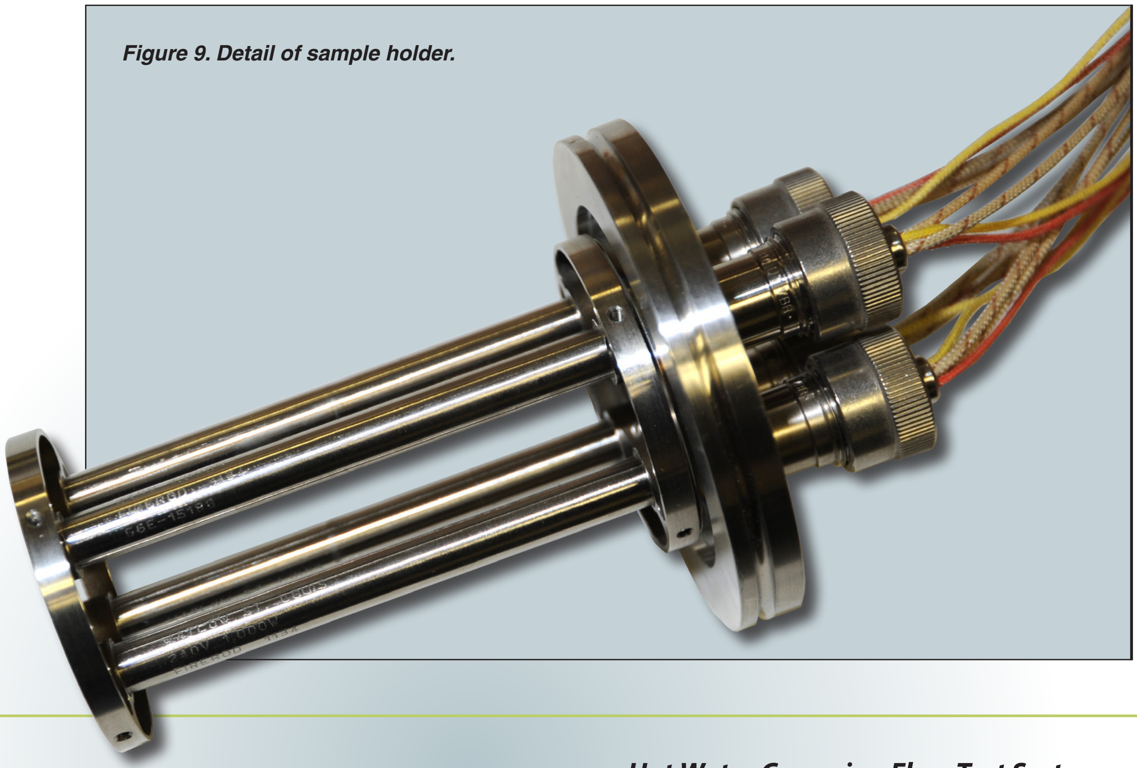

Figure 9. Detail of sample holder.

performance conditions relative to standard zirconium-based cladding:

1. Decreased hydrogen uptake (corrosion)
2. Decreased fretting of the cladding tube under normal operating and postulated accident conditions.

Typical characterization tests will quantitatively measure the material density, thermal expansion behavior, thermal conductivity, electrical resistivity, strength at temperature, hardness, fatigue properties, as-fabricated microstructure, porosity, and chemical reactivity with the coolant under nominal and postulated off-nominal conditions (other tests/measurements added as needed). Tests also must be designed to specifically assess possible chemical interaction between the uranium dioxide fuel kernel and the proposed cladding material. Cold characterization testing will establish baseline properties in advance of any future irradiation testing. These data will be compared to the current zirconium-based cladding in operating LWRs to inform the downselection process for an advanced clad system.

Full characterization of cladding materials and designs will require a variety of test equipment and will encompass both non-destructive and destructive testing. An example of one of the unique, engineering-scale test systems that has been designed and built for application in the LWRS Program is the hot water corrosion flow (HWCF) test system.

Hot Water Corrosion Flow Test System

The LWRS Program has set up a HWCF test system at the Idaho National Laboratory to characterize the thermal, chemical, and structural properties of candidate advanced fuel cladding materials and designs under a variety of simulated flow and internal heating conditions to mimic operational reactor conditions. A diagram of the HWCF test system is provided in Figure 6, a photo of the test system is provided in Figure 7, with details of the sample holder provided in Figures 8 and 9. Water conditions are set to be representative of reactor primary coolant chemistry and fluid flow. Internal cartridge heaters, installed inside the unfueled rodlets to simulate heat produced by fission, will be used for thermal stress experiments.

The HWCF test system is designed to expose cladding materials to heated, pre-conditioned water ranging from 40 to 180°F (278 to 355 K), less than 25 psig (0.17 MPa), and water flow rates ranging from 0.01 to 40 ft/s (0.003 to 12 m/s). High-purity water introduced in the closed-loop system will range from a pH of approximately 5 to 8, depending on the specific test requirements. A temperature-controlled hot water immersion heater designed for prolonged operation preheats the water to the desired temperature at the inlet to the rodlet test section. A controllable, high-capacity water pump is used to maintain water flow conditions within the stainless steel piping system. A heat exchanger and chiller are incorporated to ensure that water temperature at the inlet to the test section does not exceed the desired level. The water flow rate, pressure, and temperature are measured

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continuously during testing. Water chemistry, pH, and oxygen content are measured periodically via analysis of water samples taken from the test loop (see Figure 6 for water sample location).

The HWCF test system is designed for the following two modes of operation:

1. Corrosion-only: heated water without internal rodlet heating
2. Thermal stress: heated water with internal rodlet heating.

The corrosion-only tests can be run in an automatic or an "unattended" condition for long periods of time (e.g., hours/days/weeks) with minimal operator supervision, while automatically recording relevant data from system sensors. Operator pre-set alarms and safety interlocks are used to activate water pump and heater shutdown should an off-normal event occur (such as a power outage or water leakage). Set points are established for water level, temperature, pressure, and flow rate.

Thermal stress tests incorporate internal cartridge heaters to impart thermal stress to the tube walls, similar to the conditions in an operating reactor. Thermal stress tests require manual operation to vary the internal rodlet temperature via heater current adjustments. Individual heater elements can be operated at up to 1 kW.

Data from the HWCF tests will support downselection of advanced cladding material and design and will provide baseline data for future evaluation of clad performance under irradiation. Operational testing of the HWCF test system has been initiated. Basic flow and heat-up profiles are being performed to test the integrity of the piping system, components, and safety features. A dry run with clad pre-prototypes is scheduled for May 2012. The test run will include a Zircaloy-4 tube for baseline measurements and two SiC CMC hybrid tubes (SiC CMC external with Zircaloy-4 liner tube). The pre-prototype testing will provide an opportunity for operator training and will establish standard test procedures.

Path Forward

The LWRS Program Fuel Development Plan will be finalized in the third quarter of Fiscal Year 2012. The Fuel Development Plan will highlight the most promising options for advanced clad and structural materials and will outline a plan for fabrication and testing to support downselection of the material composition, fabrication methods, and assembled design. The HWCF test system will be fully demonstrated using pre-prototype SiC CMC clad designs in advance of introducing alternate design candidates into the test section. A steam test loop intended to assess advanced clad design performance under postulated accident conditions currently is being designed and is planned for construction and operation by the end of Fiscal Year 2012. Other tests, including bend and burst tests for tubular clad samples, also are under development in Fiscal Year 2012.

Recent LWRS Milestones

- ***Long-Term II&C Modernization Future Vision and Strategy***

  https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/Long-Term%20IIandC%20Modernization%20Future%20Vision%20Strategy%20Rev%201.pdf

Editor: Teri Ehresman
Writer: LauraLee Gourley

To submit information or suggestions, contact Cathy J. Barnard at **Cathy.Barnard@inl.gov**.